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INVESTIGATION OF THE IONOSPHERIC SHORT-TERM VARIABILITY

Final Technical Report

by

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ABSTRACT

Reliable HF communictions require propagation assessment. Such assessment could be facilitated with the monitoring of ionospheric characteristics by continuously available passive means, i.e, measurements of the total electron content(TEC) using satellite-emitted signals without a need for burdening the electromagnetic spectrum. With the Global Positioning System (GPS) providing instantaneous time delay, or equivalently, TEC, values when needed, an assessment of HF propagation may be available on a near realtime basis.

To assess this possibility a one year study of the correlation between TEC and foF2 using GPS time delay observation taken at Matera, Italy was undertaken during 1995-1996. This is a period of minimum solar activity with sunspot numbers varying between 6-18. The observed correlation coefficient varied between 0.55 in the winter of 1996 to about 0.75-0.8 during the summer of 1995.

In addition to the seasonal variability of the correlation coefficient, a diurnal variability is also present with the coefficient normallly maximizing during the day and minimizing in the predawn periods. The predawn minimum may be due to the contribution of plasmaspheric electron content. The correlation coefficient appears to increase with magnetic activity, indicating that TEC and foF2 behave similarly during magnetically active periods. Distribution of errors between measured foF2 values and predicted ones using a) standard predictions algorithms and b) TEC measurements converted to foF2 from a model of slab thickness, show that the errors are reduced when using TEC observations. The errors would be further reduced if the satellite subionospheric point would approach the location of the foF2 actual measurements.

KEY WORDS

Ionospheric variability; HF propagation; HF short-term predictions; Total electron content (TEC); foF2; Transionospheric time-delay; GPS.

TABLE OF CONTENT

1. INTRODUCTION

HF radio communication depends on the ability of the ionosphere to return the radio signal incident on it back to Earth. Predictions of ionization levels in the various ionospheric regions are derived from models and are used as a basis for planning and frequency management of HF radio systems worldwide. Uncertainties or inaccuracies in the models of the ionosphere have long been known to be one of the major causes if not the major cause, for inaccuracies in the calculated propagation characteristics. This is particularly true for those applications of ionospheric predictions involving timescales that are less than the monthly average or monthly median.

To reduce average monthly RMS errors in predictions, adaptive techniques that use real-time observations to correct model biases have been devised. A method that is potentially global in nature involves the monitoring of satellite-emitted signals which yield information on the ionospheric parameters along the propagation path such as time-delay or TEC and converting such information into the HF propagation parameters of interest (foF2). The advantage of monitoring satellite-emitted signals is the fact that it is passive for the potential user, and the existence of a global network of satellites (e.g., the Global Positioning System, or GPS) affords the possibility of global coverage.

To assess the possible improvement of HF short-term predictions from transionospheric measurements, a correlation study between TEC daily variability about the monthly mean and foF2 variability was undertaken. Earlier studies utilized TEC data from Israel and foF2 measurements from Cyprus. The results of these studies were reported and published in various scientific conferences [1],[2],[3],[4],[5], scientific journals [6] and the Final Technical Report of contract DAJA-93-C-0035 [7]. Recently one year of foF2 and TEC data from Italy were used to study the diurnal and seasonal effects on the correlatiom and its dependence on magnetic activity.

2. EXPERIMENTAL DATA

The foF2 data were deduced from vertical ionograms taken at Rome, Italy (41.9°N, 12.5°E), using the Digisonde 256. The GPS observations were taken at Matera, Italy, a site of the International GPS service (IGS).

The equivalent TEC from the time delay measurements was determined only for satellites at elevations larger than 30° and having a subionospheric point along the line of sight within ±5° of the latitude and longitude of the digisonde. The 5-min observed time delays were then corrected for satellite biases using the Jet Propulsion Laboratory (JPL) table of corrections, converted into vertical TEC and averaged to obtain hourly values.

For each month of observations, the hourly values of the variability of both the TEC and foF2 were determined. The variability is calculated by substracting the monthly average value from each hourly value and dividing by the monthly avarage value. The TEC and foF2 variabilities and the results of the cross-correlation analysis betweem foF2 and TEC for the period June 1995 - May 1996, are given in Final Technical Report, contract N68171-95-c-9028 [8].

3. CORRELATION RESULTS

The results of the study of the diurnal, seasonal and magnetic activity effects of the correlation between foF2 and the TEC during 1995-1996 are presented in the following paper:

H. Soicher and Z. Houminer: "Determination of foF2 short-term variations from GPS time delay observations." [9]. The paper is reproduced in Appendix A and the summary of the results are presented in this section.

1995-1996 was a period of minimum solar activity with sunspot mumbers varying between 6-18. The observed correlation coefficient varied between 0.55 in the winter of 1966 to about 75-0.8 during the summer of 1995. In addition to the seasonal

variability of the correlation coefficient, a diurnal variability is also present with the coefficient normally maximizing during the day and minimizing in the predawn periods. The predawn minimum may be due to the contribu-tion of plasmaspheric electron content. The correlation coefficient appears to increase with magnetic activity, indicating that TEC and foF2 behave similarly during magnetically active periods. Distribution of errors between measured foF2 values and predicted ones using a) standard predictions algorithms and b) TEC measurements converted to foF2 from a model of slab thickness, show that the errors are reduced when using TEC observations. The errors would be further reduced if the satellite subionospheric point would approach the location of the foF2 actual measurements.

4. CONCLUSIONS

The high cross-correlation for foF2 and TEC in the one year data presented here raises the possibility that real time TEC measurements may be used to update foF2 value determinations. The cross-correlation may even be higher if the geographic subionospheric point of TEC measurements is close to the geographic point of the foF2 measurement which introduces an error, in addition to the possible inherent measurement uncertainties. The correlation exhibits diurnal and seasonal variability reaching maxima during summer day and minima at all seasons during the predawn period. The data were taken near the minimum phase of the solar cycle, during which phase the plasmaspheric electron content was expected to be of the order of the ionospheric content at predawn periods and thus affect the correlation.

The fact that the correlation during the maximum phase (Houminer and Soicher 1996) is not markedly different from the correlation at minimum phase presented here, indicates that the plasmaspheric content does not impact the correlation in a significant way. The cross-correlation is high during magnetically active periods indicating that foF2 and TEC behave similarly in response to geomagnetic activity.

Global GPS Constellation can provide instantaneous time-delay, or TEC, values which could provide an instantaneous updating of foF2 models on a global basis as well as on a regional basis. The GPS signals are passive in nature to the user and, as such, do not burden the electromagnetic spectrum.

5. LIST OF PUBLICATIONS

[1] Z. Houminer & H. Soicher, "Improvement of foF2 short-term predictions from transionospheric time-delay measurements." National Radio Science Meeting, University of Colorado, Boulder, 5-8 January 1994.

[2] H. Soicher & Z. Houminer, "Real-time ionoshperic HF prediction improvements by passive means." 19th Army Science Conference, Orlando, Florida, 20-23 June 1994.

[3] Z. Houminer & H. Soicher, "Assessment of foF2 short-term variations from GPS time-delay measurements." International Beacon Satellite Symposium, Aberystwyth, Wales, 11-15 July 1994.

[4] H. Soicher & Z. Houminer,"Passive HF propagation evaluation technique". AGARD Conference Proceedings 574, April 1996.

[5] Z. Houminer & H. Soicher, "Improved short-term predictions of foF2 using GPS time-delay measurements." Ionospheric Effects Symposium, Alexandria, VA, USA, 7-9 May 1996.

[6] Z. Houminer & H. Soicher, "Improved short-term predictions of foF2 using GPS time-delay measurements." Radio Science, 31, 1099-1108, 1996.

[7] Z. Houminer, "Investigation of the ionospheric short-term variability", Final Technical Report, October 1994.

[8] Z. Houminer, Investigation of the ionosperic short-term variability, Final Technical Report, February 1997.

[9] H. Soicher and Z. Houminer, "Determination of foF2 short-term variations from GPS time delay observations", Acta Geod. Geoph. Hung., 33, 111-119, 1998.

APPENDIX A

H. Soicher and Z. Houminer, "Determination of foF2 short-term variations from GPS time delay observations".

Acta Geodaetica et Geophysica Hungaria, Volume 33, number 1, pp 111-119, 1998.

Acta Geod. Geoph. Hung., Vol. 33(1), pp. 111–119 (1998)

DETERMINATION OF f_0F2 SHORT-TERM VARIATIONS FROM GPS TIME DELAY OBSERVATIONS

H SOICHER[1] and Z HOUMINER[2]

Reliable HF communications require propagation assessment. Such assessment could be facilitated with the monitoring of ionospheric characteristics by continuously available passive means, i.e., measurements of the total electron content (TEC) using satellite-emitted signals without a need for burdening the electromagnetic spectrum. With the Global Positioning System (GPS) providing instantaneous time delay, or equivalently, TEC, values when needed, an assessment of HF propagation may be available on a near realtime basis.

To assess this possibility a one year study of the correlation between TEC and f_0F2 using GPS time delay observations taken at Matera, Italy and f_0F2 measurements from Rome, Italy, was undertaken during 1995–1996. This is a period of minimum solar activity with sunspot numbers varying between 6–18. The observed correlation coefficient varied between 0.55 in the winter of 1996 to about 0.75–0.8 during the summer of 1995.

In addition to the seasonal variability of the correlation coefficient, a diurnal variability is also present with the coefficient normally maximizing during the day and minimizing in the predawn periods. The predawn minimum may be due to the contribution of plasmaspheric electron content. The correlation coefficient appears to increase with magnetic activity, indicating that TEC and f_0F2 behave similarly during magnetically active periods. Distribution of errors between measured f_0F2 values and predicted ones using a) standard predictions algorithms and b) TEC measurements converted to f_0F2 from a model of slab thickness, show that the errors are reduced when using TEC observations. The errors would be further reduced if the satellite subionospheric point would approach the location of the f_0F2 actual measurement.

Keywords: f_0F2; TEC; variability slab thickness

1. Introduction

HF radio communication depends on the ability of the ionosphere to return the radio signal incident on it back to Earth. Predictions of ionization levels in the various ionospheric regions are derived from models and are used as a basis for planning and frequency management of HF radio systems world-wide. The models permit the calculation of system parameters such as operating frequencies, signal strengths, signal-to-noise ratios, and multipath probability that can be used to describe the performance of HF radio systems. Uncertainties or inaccuracies in the models of the ionosphere have long been known to be one of the major causes if not the major cause, for inaccuracies in the calculated propagation characteristics. This is particularly true for those applications of ionospheric predictions involving timescales that are less than monthly average or monthly median.

To reduce average monthly RMS errors in predictions, adaptive techniques that use real-time observations to correct model biases have been devised. A method that

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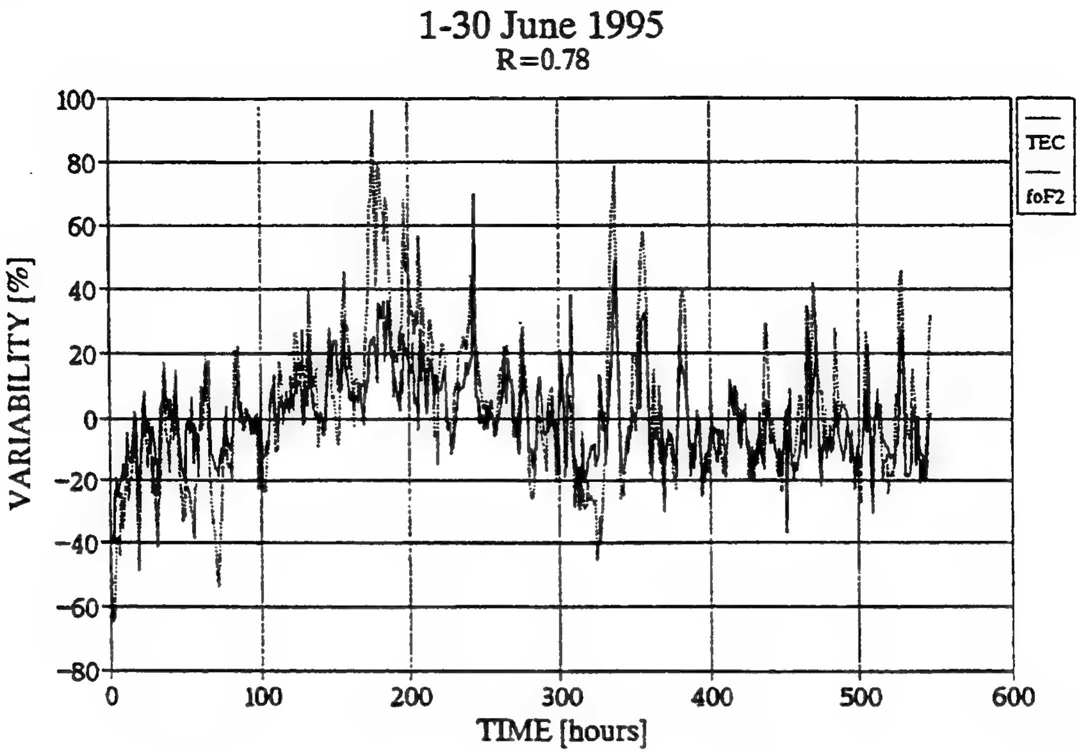

Fig. 1. Hourly values of variability of f_0F2 and TEC for June 1995. R is the cross-correlation coefficient at zero time lag

is potentially global in nature involves the monitoring of GPS signals which yield information on the ionospheric parameters along the propagation path and converting such information into the HF propagation parameters of interest. The advantage of monitoring GPS signals is the fact that it is passive for the potential user, and the existence of a global network of satellites affords the possibility of global coverage. The problem at hand is the conversion of integrated ionospheric parameters along the transionospheric path experienced by the GPS signal to the parameters along the path experienced by the HF sky wave up to the point of reflection from the ionospheric layers. A parameter of great importance in HF propagation is f_0F2, the upper frequency limit for ordinary mode HF vertical propagation, whose square is proportional to $N_{\max}$, the maximum electron density in the ionosphere. The transionospheric parameter of importance is the total electron content (TEC), which is the integrated electron density along the propagation path of a satellite-emitted signal to the observer (TEC $= \int N ds$, where N is the electron density and ds is an element of distance along the path from observer to satellite). Since both TEC and $N_{\max}$ vary diurnally, seasonally, geographically, and in response to magnetic activity, it is expected that their ratio, the so-called slab thickness, τ, will vary to a lesser degree and hence can be modeled more easily. Global models of slab thickness updated with real-time measurements of TEC might possibly yield improved values of $N_{\max}$ and hence f_0F2 for HF propagation.

To test the efficacy of this hypothesis, one has to ascertain the correlation be-

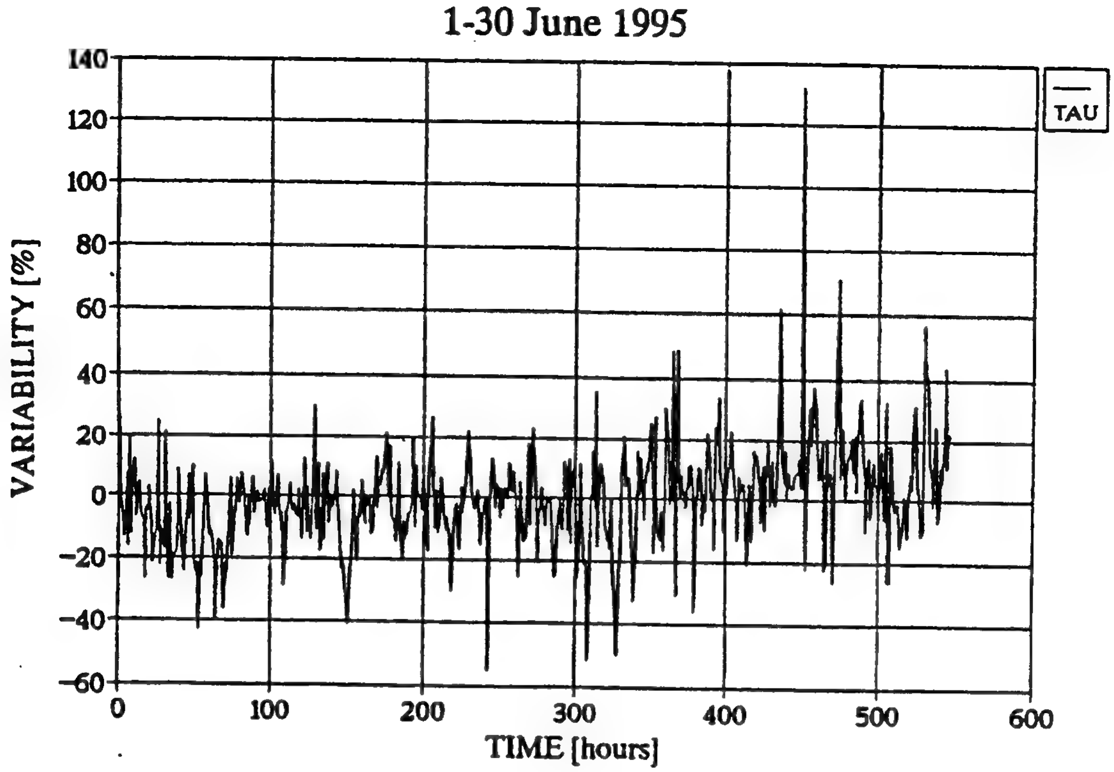

Fig. 2. Hourly values of the variability of τ (Slab Thickness) for June 1995

tween the TEC daily variability about the monthly mean and the f_0F2 variability. Further, diurnal, seasonal and response to magnetic activity effects on such correlation have to be assessed.

2. Experimental data

The f_0F2 data were deduced from vertical ionograms taken at Rome, Italy (41.9°N, 12.5°E) using the Digisonde 256 (Soicher et al. 1995). The GPS observations were taken at Matera, Italy, a site of the International GPS Service (IGS).

The equivalent TEC from the time delay measurements was determined only for satellites at elevations larger than 30° and having a subionospheric point along the line of sight within ±5° of the latitude and longitude of the digisonde. The 5-min observed time delays were then corrected for satellite biases using the Jet Propulsion Laboratory (JPL) table of corrections (Wilson and Mannucci 1993), converted into vertical TEC (Klobuchar 1987) and averaged to obtain hourly values.

For each month of observations, the hourly values of the variability of both the TEC and f_0F2 were determined. The variability is calculated by subtracting the montly average value from each hourly value and dividing by the monthly average value. An example showing the hourly values of the variability of f_0F2 and TEC for the period 1–30 June, 1995 is shown in Fig. 1. This period is near the minimum phase of solar cycle 22. It can be seen that there is good correlation between the variability of f_0F2 and TEC.

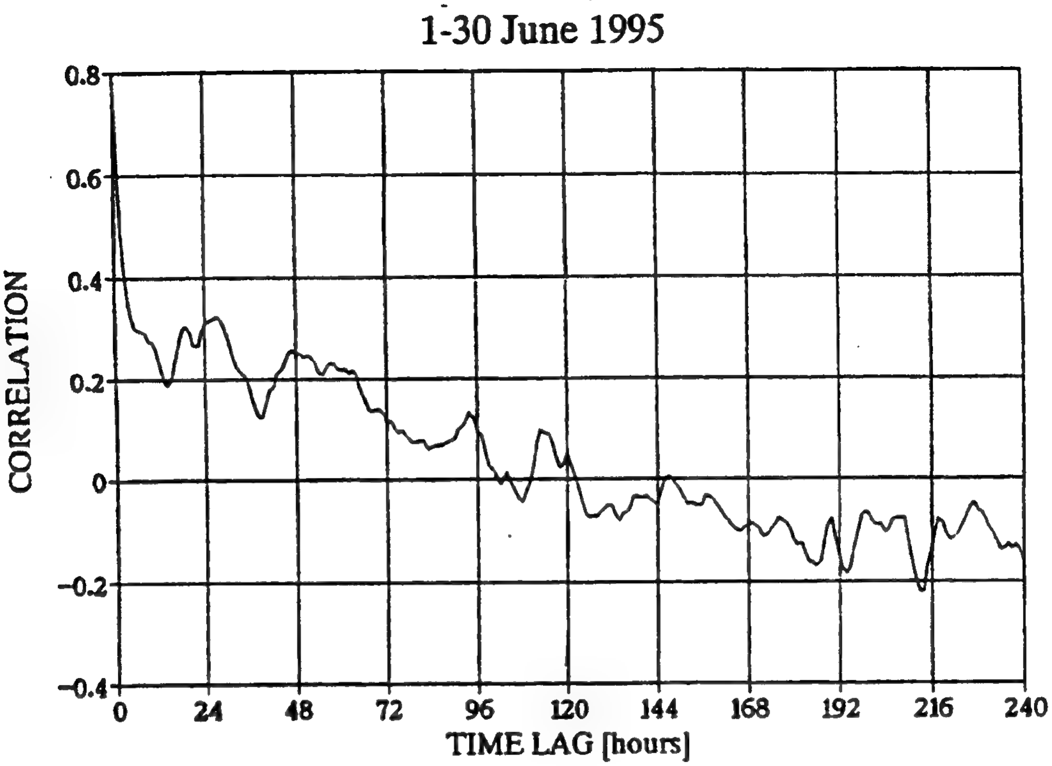

Fig. 3. Cross-correlation function of f_0F2 and TEC values of Fig. 1 (June 1995)

Another parameter of interest is the slab thickness, τ, which is proportional to the ratio TEC/$(f_o\mathrm{F2})^2$. The slab thickness can be calculated for each hour of observations and its variability determined in the same way as for TEC or f_0F2. The variability in τ for the period June 1995, is shown in Fig. 2. It can be seen that the variability is of the order of the corresponding variability of TEC or f_0F2.

3. Correlation results

The results of cross-correlation analysis on the f_0F2 and TEC variabilities depicted in Fig. 1 are shown for a portion of the time in Fig. 3. A maximum cross-correlation coefficient, R, of 0.78 occurs at zero time lag, and the coefficient reduced very quickly with time lag. It is thus shown that the correlation between f_0F2 and TEC is very good. A 24-hour periodicity, at least for the first 48 hours, is observed.

It can be seen from Fig. 1 that both the variations of f_0F2 and TEC are rather noisy on an hour-to-hour basis, which may be caused by measurements and data reduction errors rather than by physical phenomena. The main reason for these errors are (1) combining measurements from various GPS satellites, each with a different orbit and bias, which introduces errors (Klobuchar et al. 1994), (2) errors introduced by converting from oblique TEC measurements to vertical values, especially at times when there are large ionospheric horizontal gradients, and (3) real-time scaling of f_0F2 data, which introduces errors. The results of smoothing the variations in TEC and f_0F2 by a 3-hour running mean are shown in Fig. 4. It

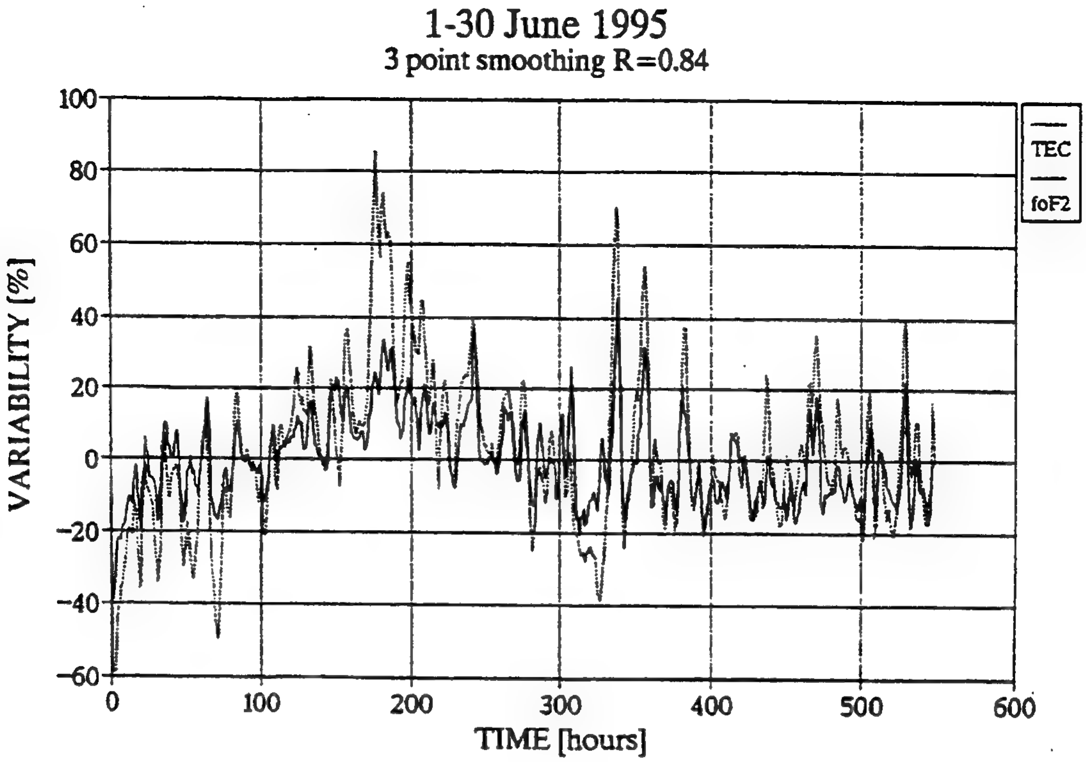

Fig. 4. Three-hour smoothing of the f_0F2 and TEC values of Fig. 1

can be seen that the correlation is improved (R of 0.84). This shows that indeed the data are noisy and that the correlation betwen TEC and f_0F2 is actually better than what the raw data indicate.

Cross-correlation results for the 12 months period, June 95 through May 96, for both the mean raw and the smoothed (3-hour running mean) are shown in Fig. 5. The overall trend is towards a $\sim$ 20% decrease in the cross-correlation coefficient, and this may reflect the corresponding decrease in sunspot numbers from 18 to 6.

The diurnal variations of the correlation coefficients for two summer periods, 1992 and 1995, are shown in Fig. 6. The 1992 period is near solar maximum phase, while the 1995 period is near the minimum phase. Each point in the figure represents correlation results for a 4-hour block (for example, the correlation at 0800 LT gives the results for the time block 0600–1000 LT). It can be seen that the diurnal behaviour is very similar for the two periods. There are minima, at about 0800 LT. A broad maximum in correlation occurs between 1200–2000 LT, with values as high as 0.85.

The similarity of the diurnal variation, especially at the predawn period minima, may be due to the minor role of plasmaspheric electron content in the correlation results. During solar maximum the plasmospheric content appears not to affect the correlation (Houminer and Soicher 1996).

The seasonal dependence of the diurnal variation of the correlation coefficient between the variability in TEC and f_0F2 is shown in Fig. 7. It can be seen that

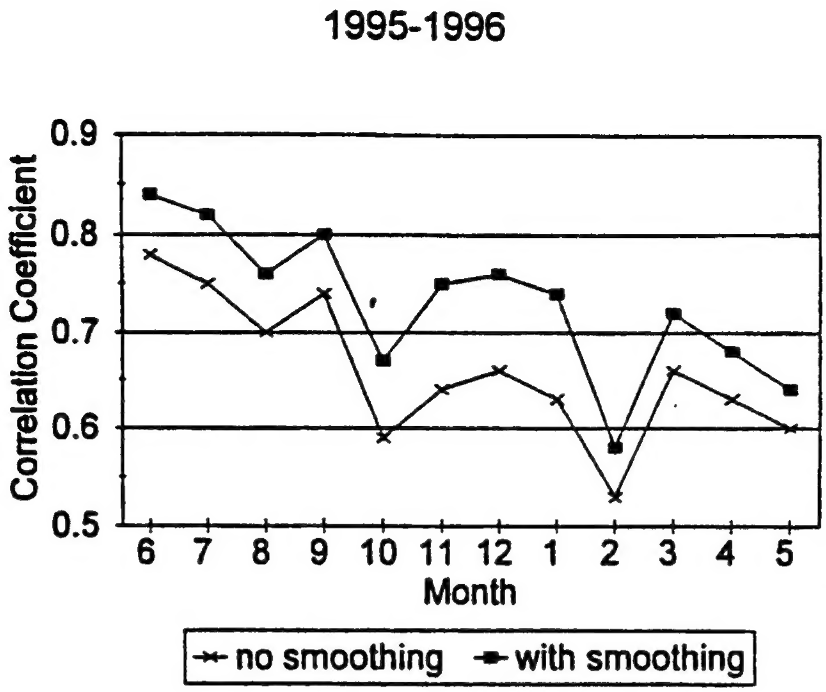

Fig. 5. Unsmoothed and smoothed mean monthly cross-correlation coefficient values of the 12-month period, June 1995 to May 1996

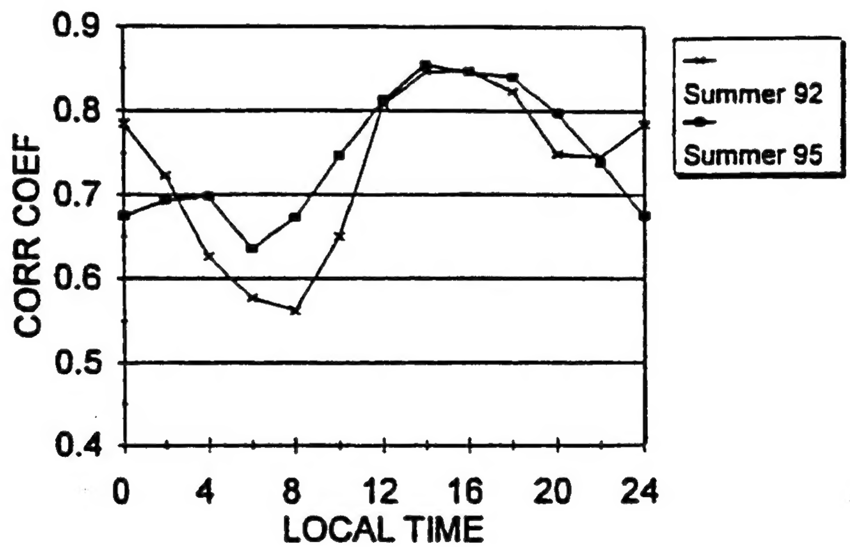

Fig. 6. Diurnal variation of the cross-correlation coefficient for f_0F2 and TEC values for the summer periods of 1992 and 1995. Each point represents correlation results for a 4-hour period

the correlation coefficient maximizes in summer, shows similar variation during the equinoxes and shows little variation during winter.

The ionosphere is known to vary substantially with geomagnetic activity. To ascertain whether magnetic activity has any impact on the cross-correlation of f_0F2

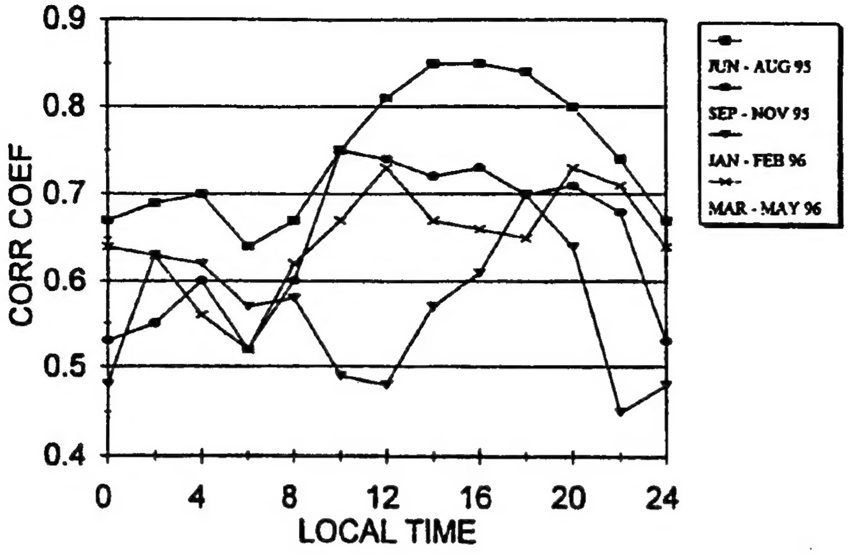

Fig. 7. Seasonal dependence of the diurnal variation of the cross-correlation coefficients for f_0F2 and TEC values. Each point represents correlation results for a 4-hour period

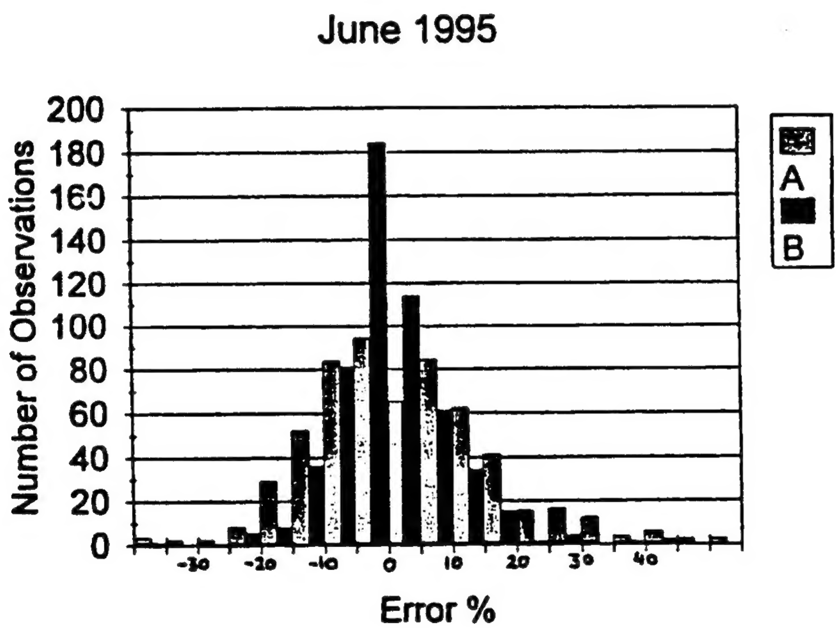

Fig. 8. Error distribution of f_0F2 calculated from TEC (dark bars) and obtained from standard model (light bars) from measured f_0F2 values (see text)

and TEC, data were compared between quiet and active periods. Table I shows selected periods with $32 < A_p < 57$ and $A_p < 8$. The correlation coefficient R for the selected period is compared with R^*, the monthly correlation coefficient containing the selected period.

It is seen that during the active periods the correlation coefficient is normally greater than that of the monthly one, whereas for quiet selected periods it is not

Table I. Cross-correlation coefficients R for selected time periods of quiet and active geomagnetic activity. R^* are the overal monthly coefficients which include the selected time periods

Dates	A_p	R	R^*
25–29 Sep 1995	41	0.80	0.74
03–08 Oct 1995	57	0.64	0.59
17–21 Oct 1995	34	0.63	0.59
18–23 Mar 1996	38	0.65	0.66
13–22 Apr 1996	32	0.74	0.63
04–15 Jun 1995	≤ 8	0.82	0.78
04–15 Jul 1995	≤ 8	0.77	0.75
25–29 Oct 1995	≤ 8	0.55	0.59
13–26 Nov 1995	≤ 8	0.58	0.64

necessarily so. The conclusion drawn is that magnetic activity affects TEC and f_0F2 in similar manner (Mendillo et al. 1972), thus maintaining high cross-correlation between the two.

The slab thickness, τ, is proportional to the ratio TEC/$(f_o\mathrm{F2})^2$. It is expected that the variability of τ will be somewhat smaller than the variability of either the TEC or f_0F2 because of the good correlation between these two ionospheric parameters. Thus global models of the slab thickness, updated with real-time measurements of TEC obtained with the GPS network, might give improved values of f_0F2.

In order to explore this possibility, f_0F2 values for each hour were calculated using TEC obtained from the GPS time delay observations and slab thickness values from the global model of Fox et al. (1991). The error distribution for f_0F2 derived from standard prediction algorithms, and f_0F2 derived from measured TEC and the τ model are shown in Fig. 8. It is seen that the f_0F2 errors are smaller with the use of TEC measurements and the slab thickness model.

4. Conclusions

The high cross-correlation coefficient for f_0F2 and TEC in the one year data presented here raises the possibility that real-time TEC measurements may be used to update f_0F2 value determinations. The cross-correlation may even be higher if the geographic subionospheric point of TEC measurement is close to the geographic point of the f_0F2 measurement which introduces an error, in addition to the possible inherent measurement uncertainties. The correlation exhibits diurnal and seasonal variability reaching maxima during summer day and minima at all seasons during the predawn period. The data were taken near the minimum phase of the solar cycle, during which phase the plasmaspheric electron content was expected to be of the order of the ionospheric content at predawn periods and thus affect the correlation.

The fact that the correlation during the maximum phase (Houminer and Soicher 1996) is not markedly different from the correlation at minimum phase presented here, indicates that the plasmaspheric content does not impact the correlation in a significant way. The cross-correlation is high during magnetically active periods indicating that f_0F2 and TEC behave similarly in response to geomagnetic activity.

Global GPS Constellation can provide instantaneous time-delay, or TEC, values which could provide an instantaneous updating of f_0F2 models on a global basis as well as on a regional basis. The GPS signals are passive in nature to the user and, as such, do not burden the electromagnetic spectrum.

References

Fox M W, Mendillo M, Klobuchar J A 1991: *Radio Sci.*, 26, 429–438.

Houminer Z, Soicher H 1996: *Radio Sci.*, 31, 1099–1108.

Klobuchar J A 1987: Ionospheric time-delay algorithm for single frequency GPS users. IEEE Trans. Aerosp. Electron. Syst., AES-23, 325–331.

Klobuchar J A, Doherty P H, Bailey G J, Davies K 1994: In: Proceedings International Beacon Satellite Symposium, L Kersley ed., Univ. of Wales, Aberystwyth, 1–4.

Mendillo M, Papagianis M D, Klobuchar J A 1972: *J. Geoph. Res.*, 77, 4891.

Soicher H, Gorman F J, Tsedilna E F, Weitsman O V 1995: *Radio Sci.*, 30, 755–764.

Wilson B D, Mannucci A J 1993: Instrumental biases in ionospheric measurements derived from GPS data. Paper presented at ION GPS-93, Inst. of Navig., Salt Lake City, Utah